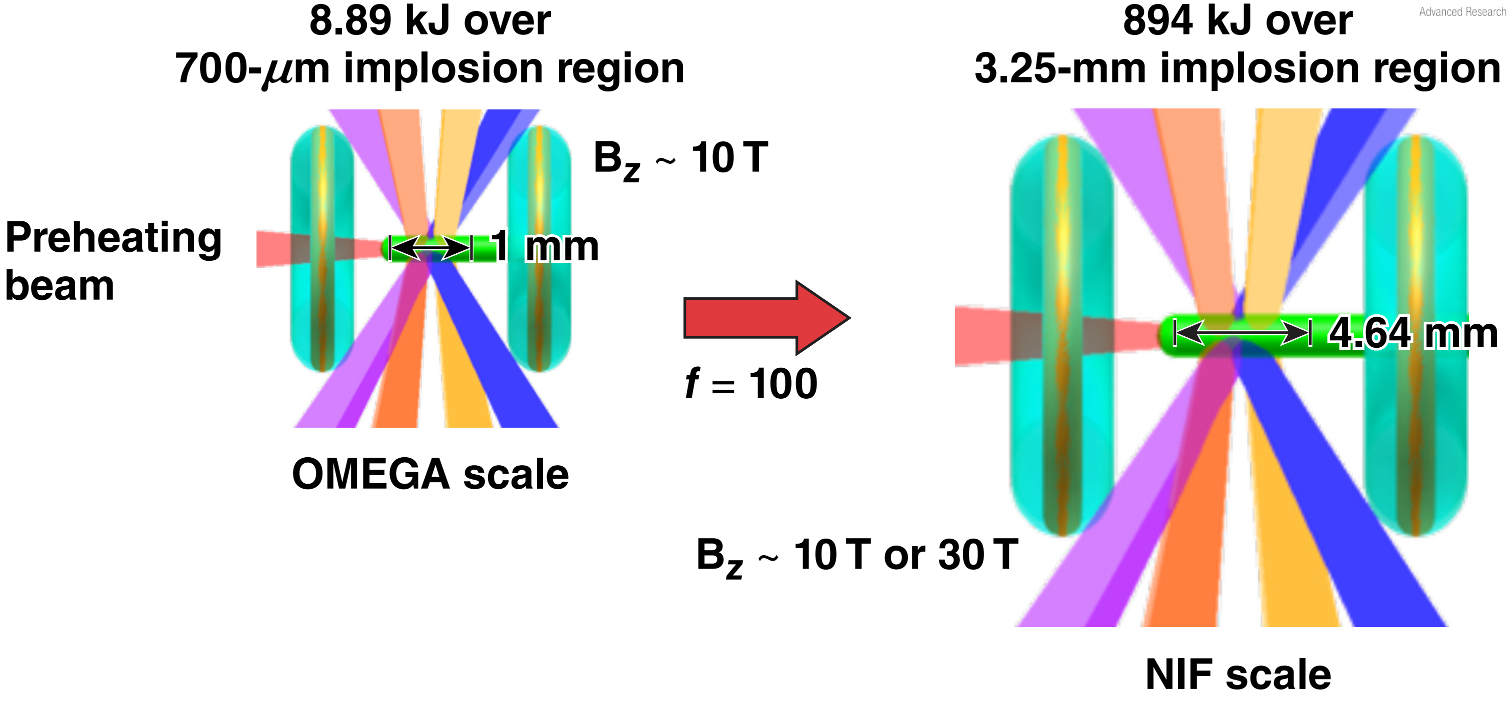
# Scaling Laser-Driven Magnetized Liner Inertial Fusion to the National Ignition Facility



8.89 kJ over
700-$\mu$m implosion region

$B_z$ ~ 10 T

Preheating
beam

OMEGA scale

*f* = 100

894 kJ over
3.25-mm implosion region

$B_z$ ~ 10 T or 30 T

NIF scale

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46th Annual Anomalous
Absorption Conference
Old Saybrook, CT
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**Summary**

# National Ignition Facility (NIF)-scale magnetized liner inertial fusion (MagLIF)* has the potential to further explore energy scaling and magnetic-field dynamics

- 1-D *LILAC* simulations were used to establish an energy scaling of the MagLIF design at NIF-relevant energies
- Conservation of magnetic flux increases with size because of a decrease in the Nernst effect at larger scale lengths
  - the Nernst effect is an additional magnetic-field–advection mechanism along a temperature gradient
- A NIF-scale target can provide magnetic confinement capable of producing a secondary DT neutron yield comparable to experiments on Z

TC12793

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* S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

# Collaborators

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Sandia National Laboratories

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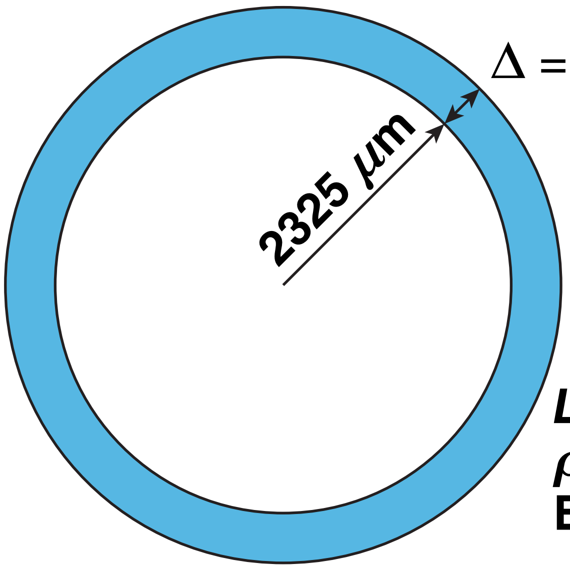
# A MagLIF point design was developed for the OMEGA laser to match energy per unit volume on Z

**Sandia target***



$\Delta$ = 465 $\mu$m Be

$L$ = 7.5 mm
$\rho$ = 0.7 to 1.5 mg/cm$^3$ D$_2$
B$_0$ = 10 T

**OMEGA target**

270 $\mu$m
$\Delta$ = 30 $\mu$m CH

$L$ = 700 $\mu$m
$\rho$ = 1.5 mg/cm$^3$ D$_2$
B$_0$ = 10 T

- The Sandia design couples ~1 MJ cm$^{-1}$ to the liner**
- OMEGA will couple ~0.01 MJ cm$^{-1}$ to a cylindrical shell
  - the shell aspect ratio is tuned to increase implosion
  - the fill density will vary from the optimal 1.5 mg/cm$^3$

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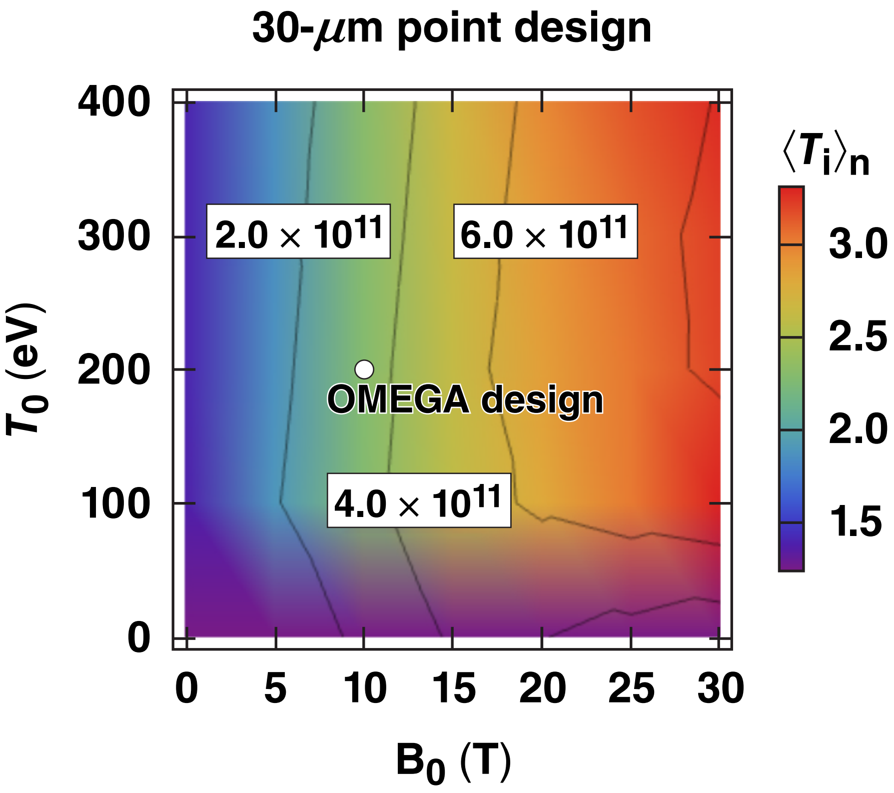
* M. R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014).
** S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

# A minimum preheat temperature of 100 eV is required for adequate yield enhancement from the magnetic field



| $B_0$ (T) | $T_0$ (eV) | $\langle T_i \rangle_n$ (keV) | $Y_n$ ($\times 10^{11}$) | CR* |
|---|---|---|---|---|
| 0 | 0 | 1.24 | 0.393 | 49 |
| 0 | 100 | 1.37 | 0.528 | 37 |
| 10 | 100 | 2.27 | 3.560 | 30 |
| 10 | 200 | 2.28 | 3.360 | 26 |

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*CR: convergence ratio

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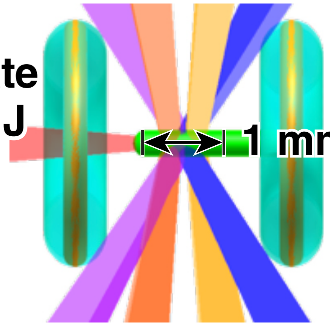
# A scaling up to NIF-relevant energies is made without reconsidering a point design specifically for the NIF

**8.89 kJ over**
**700-$\mu$m implosion region**

**200-$\mu$m**
**phase plate**
**up to 395 J**
**in 1.5 ns**



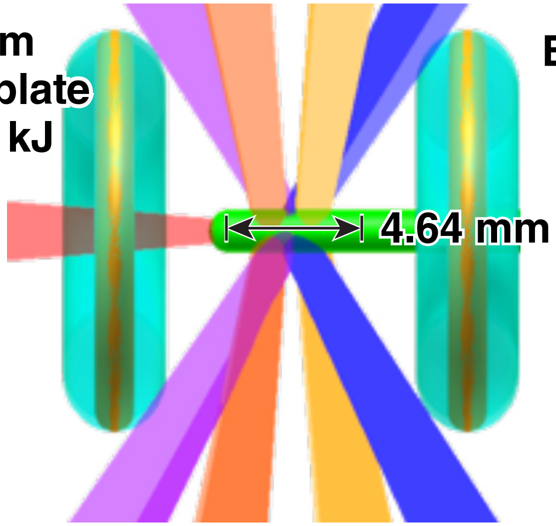
**$B_z$ ~ 10 T**

**OMEGA scale**

**$f = 100$**

**894 kJ over**
**3.25-mm implosion region**

**1000-$\mu$m**
**phase plate**
**up to 2 kJ**
**in 7 ns**



**$B_z$ ~ 10 T**
**or 30 T**

**NIF scale**

$$t \sim f^{1/3} \quad r \sim f^{1/3} \quad \ell \sim f^{1/3} \quad E \sim f$$

| | $r$ (mm) | $\Delta r$ (mm) | $r/\Delta r$ | $\rho_{\text{fuel}}$ (mg/cm$^3$) | $B_0$ (T) | $T_0$ (eV) | $V_{\text{imp}}$ (km/s) | CR | $T_{\text{max}}$ (keV) |
|---|---|---|---|---|---|---|---|---|---|
| OMEGA | 0.30 | 0.030 | 10 | 2.4 ($D_2$) | 10 | 200 | 154 | 26 | 2.9 |
| NIF | 1.39 | 0.139 | 10 | 2.4 (DT or $D_2$) | 10 or 30 | 200 | 145 | 20 | 8.5 |
| Z | 3.48 | 0.580 | 6 | 3.0 (DT) | 30 | 250 | 70 | 25 | 8.0 |

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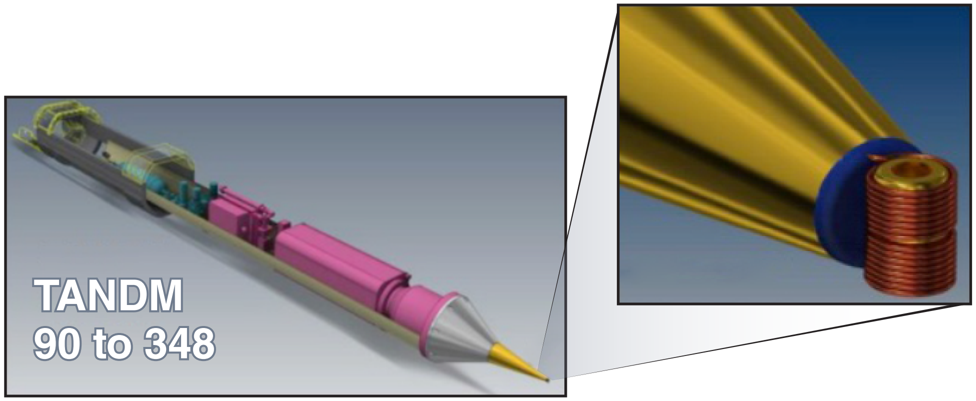
*S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

# A 30-T maximum seed field is considered as the lowest quoted magnetic field provided by a target and diagnostic manipulator (TANDM)-based pulsed-power device on the NIF*

Summary requirements

| | |
|---|---|
| B-field magnitude | 30 to 70 T |
| B-field spatial shape/extent | Axial solenoidal field within a NIF hohlraum volume |
| B-field uniformity | ~10% over capsule volume |
| B-field rise time | $\geq 1\ \mu s$ |
| Diagnostic access | Regular NIF requirements for 2dConA, Symcaps, and cryo (no keyhole required) |
| Other | Future coupling to cryo capsules |



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[*] L. Perkins *et al.*, presented at the B-Fields NIF Workshop, Lawrence Livermore National Laboratory, Livermore, CA, 12–13 October 2015.

# The neutron yield scales hydrodynamically as expected with a slight enhancement because of the magnetic field

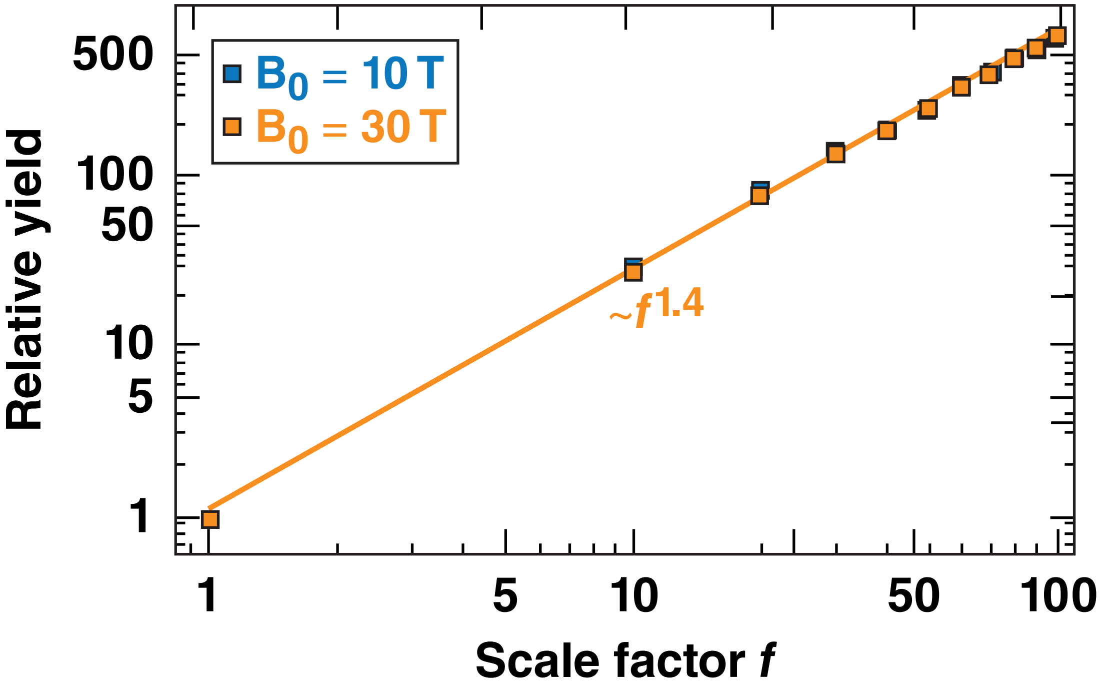
- Traditional hydro scaling*

$$Y^{n}_{1\text{-D}} \sim E^{3/2}$$

- Scaled to cylinder of defined length

$$Y^{n}_{1\text{-D}} \sim E^{3/2}\,\frac{\ell}{E} \sim E^{4/3}$$

Hydro scaling of the neutron yield



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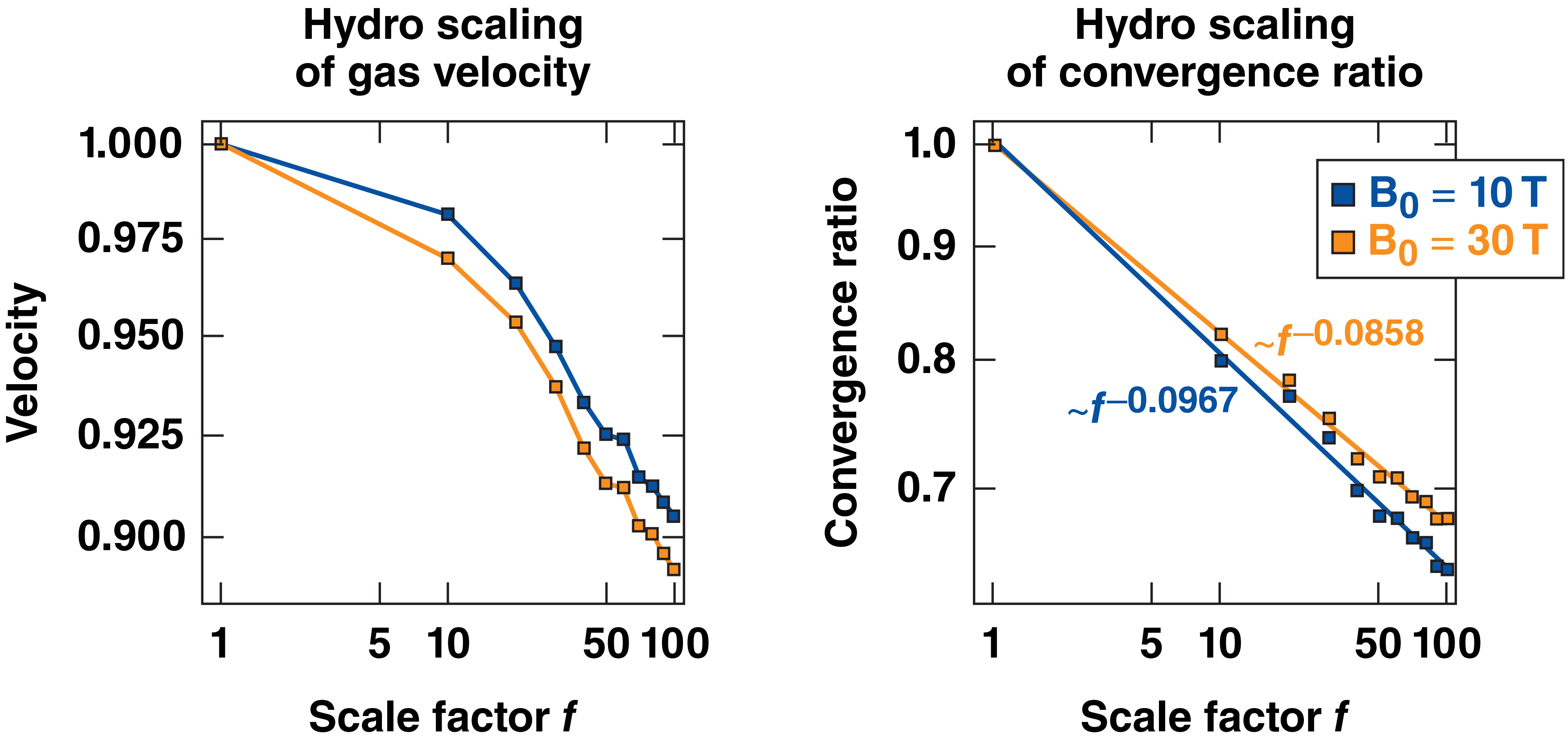
*R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

# The velocity of the outer gas region and the convergence ratio decrease with increasing scale



**NIF-scale targets must be optimized differently than OMEGA-scale targets.**

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# The thermoelectric Nernst effect convects the magnetic field like an additional velocity

- Haines* showed that Ohm’s Law can be written as

$$\vec{E} = -\vec{v}_{e} \times \vec{B} - \frac{\vec{q}_{e} \times \vec{B}}{2.5\,P_{e}} - \frac{\nabla P_{e}}{n_{e} e} + \eta \vec{j} - \beta \nabla \frac{kT_{e}}{e}$$

- Taking the curl and using Faraday’s Law

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v}_{\mathrm{eff}} \times \vec{B}\right) + \vec{v}_{\eta} \times \left(\nabla \times \vec{B}\right) + \frac{\eta_{\perp}}{\mu_{0}} \nabla^{2} \vec{B} + \frac{\nabla P_{e} \times \nabla n_{e}}{n_{e}^{2} e}$$

- Where $\vec{v}_{\mathrm{eff}}$ is

$$\vec{v}_{\mathrm{eff}} = \vec{v} - \frac{\vec{j}}{n_{e} e} + \frac{\vec{q}_{e}}{2.5\,P_{e}}$$

- The Nernst term corresponds to convection with the perpendicular electron heat flux

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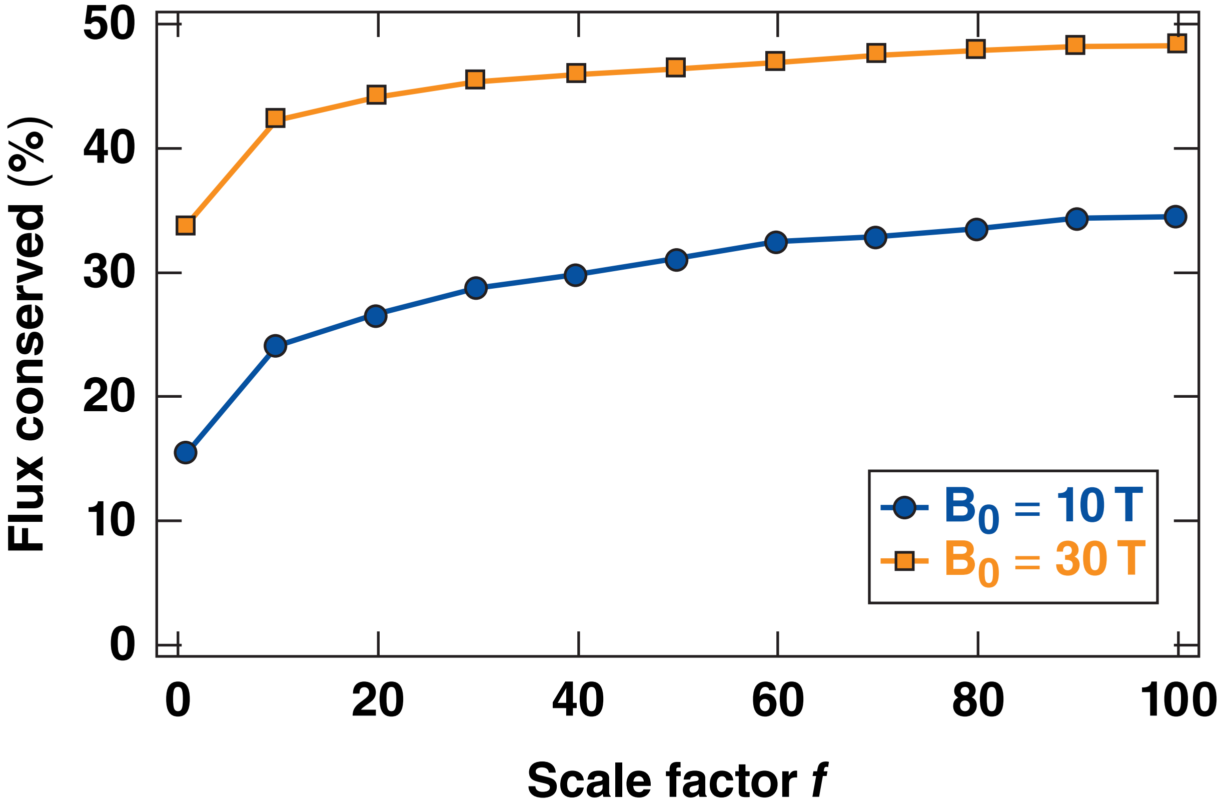
* M. G. Haines, Plasma Phys. Control. Fusion 28, 1705 (1986).

# More magnetic flux is conserved at longer scale lengths



- Longer scale lengths decrease the Nernst effect by decreasing temperature gradients
- Higher magnetic fields suppress radial heat flow, which, in turn, increases core temperature and decreases the convergence and implosion speed

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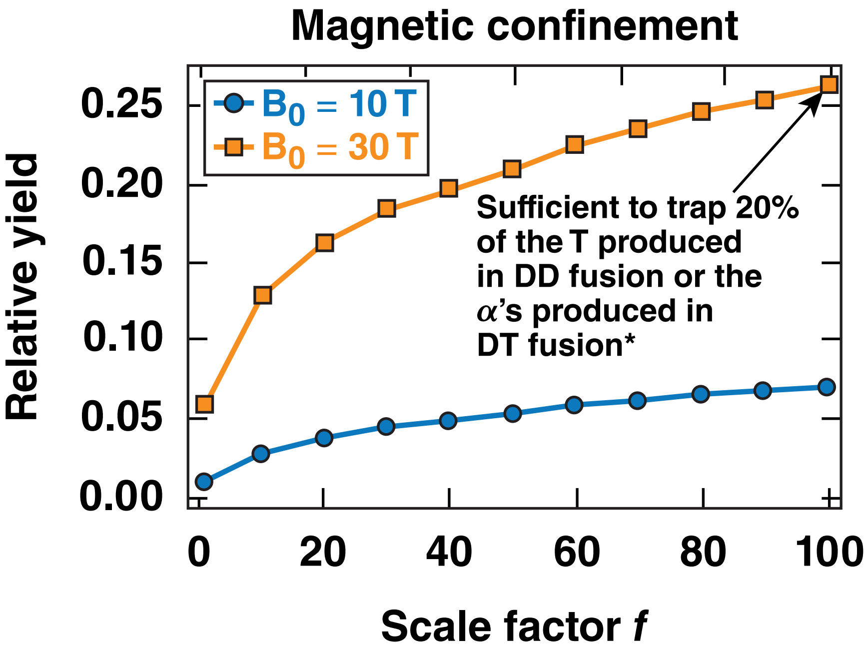
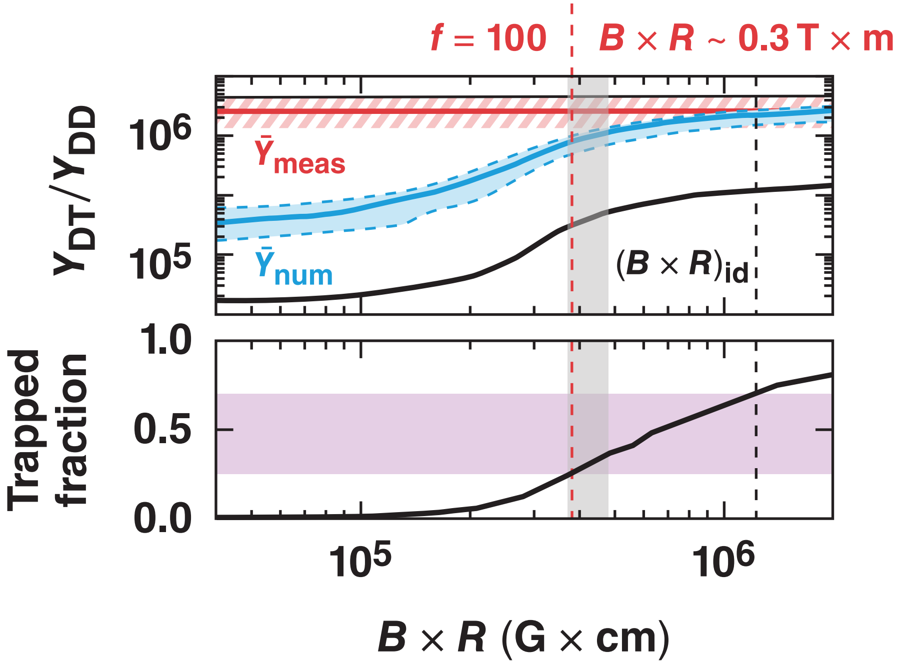
# NIF-scale MagLIF targets can have measureable triton confinement with a 30-T seed field



Sufficient to trap 20% of the T produced in DD fusion or the $\alpha$'s produced in DT fusion*



**A NIF-scale target can achieve values of magnetic confinement relevant to detectable values on Z (gray area in right graph).**

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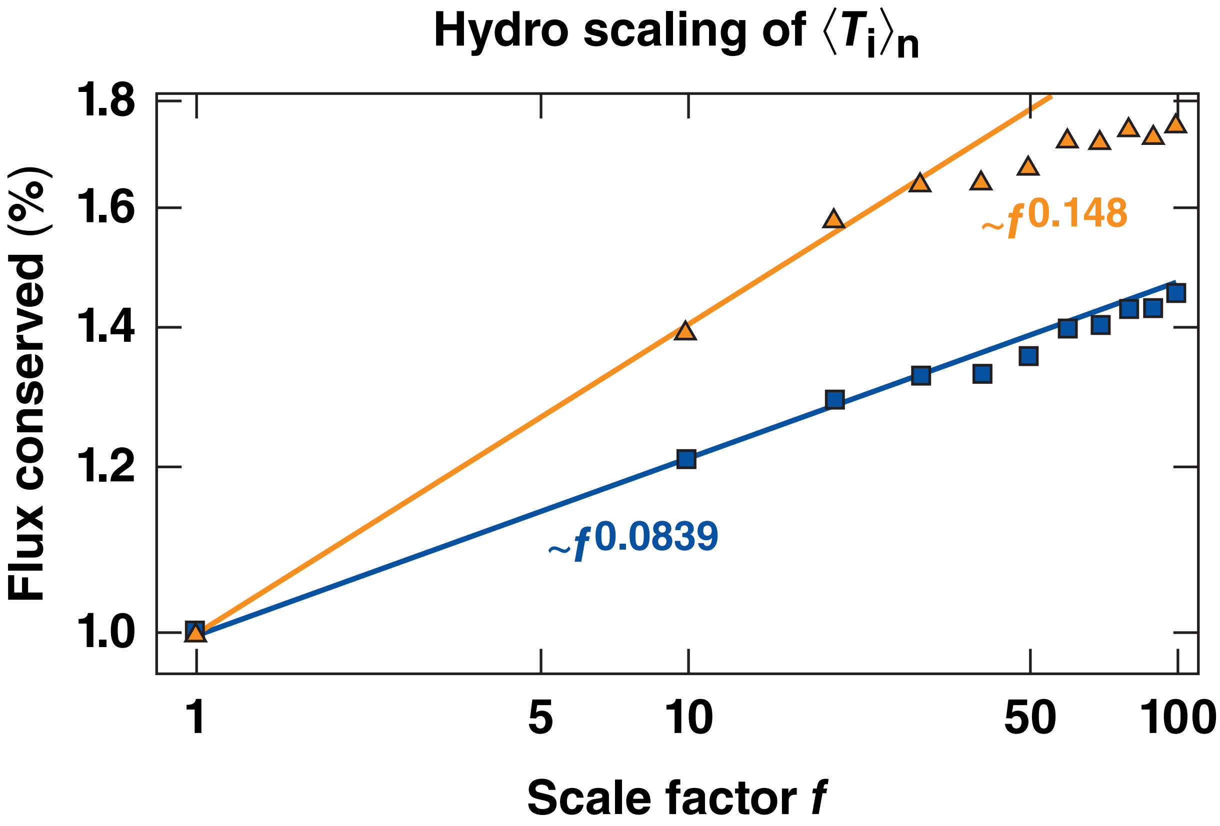
*P. F. Schmit *et al.*, Phys. Rev. Lett. 113, 155004 (2014).

# Neutron-averaged ion temperature scales weakly with energy scale



- The result of aforementioned effects is poorer scaling for the 30-T case

**A NIF-optimized design must consider the non-scalable magnetic-field effects.**

TC12801

**Summary/Conclusions**

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